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Large-scale transgressive coastal dune behaviour in Europe during the Little Ice Age

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ABSTRACT

The Little Ice Age is the most noted climatological event in recent history with dramatic consequences for a large part of the western European coastal landscape. A major morphological feature associated with this event is the presence of large-scale transgressive dune fields that actively advanced inland, encroaching, in some cases, human settlements and directly affecting coastal communities. Several hypotheses exist to explain the formation of such features, which purport increased storminess, sea-level changes, or human activities as the major drivers of the relatively well-documented *enhanced* aeolian activity during this event. However, these hypotheses do not explain entirely the whole process by which dunes are set into movement. Here, we show the temporal and spatial distribution of this event in terms of impact over the coast, focusing on the mobilization of coastal dunes and then elaborate a new conceptual model that explains the onset and evolution pathways of coastal dunes after the impact of the Little Ice Age. Our model proposes the combined effect of storms and other parameters to explain the initiation phases of the process, when sand becomes available and blown by the very strong winds associated with documented higher frequency and intensity of storms occurring during this period.

1. Introduction

Globally, most sandy coastal systems form in close association with sea-level highstands and are signatory landform features shaped by the influence of tides, local meteorological-oceanic conditions, and sources and supply of sediment. This provides an imprint of the diverse history of coastal evolution and its response to conditions through time. Yet, superimposed large-scale climate oscillations may add an additional order of complexity to coastal geomorphic systems by shifting average conditions. Globally, most active coastal systems, such as barriers, were formed around 7000 years ago after the rate of post-glacial sea-level rise decelerated. This sets the evolutionary basis of many coastal landforms during the Mid- to Late Holocene, a time period that had at least five significant climatic swings, associated with the onset of a cooling epoch identified in the North Atlantic (Bond et al., 1997; deMenocal and Bond, 1997).

The Little Ice Age (LIA) was the most recent and most documented of these events during which glaciers extended globally (Grove, 2001) and moderately cooler temperatures characterized the Northern Hemisphere from about 1400 to 1900 (Mann, 2002). The impact of this event over the Northern Hemisphere temperatures (Mann et al., 2009), sea-ice extent (Grove, 2004), glaciers and/or precipitation regimes (Nesje and Dahl, 2003) had major influence in the occurrence of major storms across the North Atlantic region (Dawson et al., 2007; Trouet et al., 2012), with particular relevance to European coasts (Fagan, 2000; Lamb and Frydendahl, 1991; Lamb, 1984). These storms have been repeatedly listed as being important drivers of dune development and active migration phases across Europe (Clarke and Rendell, 2009; Lamb and Frydendahl, 1991). Aeolian activity also presents itself as a characteristic indicator of the LIA across European coasts, including the Scandinavian peninsula (Björck and Clemmensen, 2004; de Jong et al., 2007; Nielsen et al., 2016), the German North Sea coast (Hofstede, 1991), Denmark (Aagaard et al., 2007; Clemmensen et al., 2015; Szkornik et al., 2008), Poland (Fedorowicz et al., 2012), Netherlands (Pierik et al., 2018; Wallinga et al., 2013), France (Clarke et al., 2002; Van Vliet-Lanoë et al., 2017), the British Isles (Orford et al., 2000; Wintle et al., 1998) or Portugal (Clarke and Rendell, 2006; Costas et al., 2012). Yet, many examples are not explicit on the type of dunes (i.e. regressive or transgressive dune systems) they refer to, which is in turn key to understanding the actual changes at the coast. Regressive dunes evolve synchronously with shoreline evolution, forming foredunes of diverse dimensions depending on available beach sediment (Davidson-

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Arnott et al., 2018; Psuty, 2004). Conversely, transgressive dune fields are large-scale, mobile (including denser vegetated coastal dunes) that, when active, migrate transversely, obliquely or alongshore, depending on the regional wind regime (Hesp, 2013).

Inland sand invasion during the LIA not only had a dramatic influence on the geomorphology of European coasts but also severely impacted coastal communities, burying coastal facilities and houses and overwhelming agricultural lands as documented by the numerous works on coastal archaeological sites in France (Van Vliet-Lanoë et al., 2016) or the British Isles (Bampton et al., 2017; Brown, 2015; Griffiths, 2015; Sommerville et al., 2001). It is worth highlighting that most works do not explore the actual mechanisms behind the onset of aeolian activity during this time but vaguely refer to 'environmental factors' that would likely have contributed to their migration rather than their initiation. Indeed, only a few have attempted to explain the mechanisms driving the onset of transgressive LIA coastal dunes. Aagaard et al. (2007) framed the formation and inland migration of dunes in the context of sea-level rise, a stable or slightly positive sediment budget and increased storm-surge levels favouring a transfer of large sand bars to the upper beach following storms in Denmark. This mechanism has been identified by Hesp (2013) as one of the principal scenarios of transgressive dune field development; evolving directly from the backshore. Szkornik et al. (2008), also, in a context of sea-level rise in Denmark, suggested that the main mechanism of transgressive dune formation was related to the reworking of Holocene dune ridges, highlighting the important role of the inherited morphology of emerged coastal barriers on the development of transgressive dunes. This represents the second scenario (i.e. development after foredune and/or dune field erosion) of dune development summarised by Hesp (2013). Conversely, other authors have associated falling sea levels during the LIA with the increase of sediment supply to the dunes together with strong onshore winds to instigate the formation of transgressive dunes within the eastern UK coast (Orford et al., 2000) and Denmark (Clemmensen et al., 1996).

Here, we explore the response of European coasts to the impact of changes in the environmental conditions associated with the LIA. In particular, we focus on understanding the mechanisms and drivers of aeolian activity that stimulated coastal dune rollover during this period, examining the formation and migration of transgressive dunes rather than the vertical aggradation of coastal (fore) dunes. Our objective is then to elaborate a holistic framework of coastal transgressive dunes across Europe to frame their formation within particular environmental contexts to put forward a conceptual model for the largescale inland migration of European coastal dunes during the LIA.

2. Framing the 'Little Ice Age'

The Little Ice Age (LIA) was the most recent of the millennial-scale Holocene cooling events (Bond et al., 1999) and was traceable globally although it appears to have had a larger and more pronounced impact across Europe (Mann et al., 2009). The LIA is somewhat of a misnomer as it was not, as such, an uninterrupted, globally synchronous, cold period (Matthews and Briffa, 2005; PAGES 2k Consortium, 2013; Wanner et al., 2015), although all reconstructions show generally cold conditions between 1580 and 1880, punctuated in some regions by warmer decades during the eighteenth century (PAGES 2k Consortium, 2013). Local temperature reconstructions demonstrate a notable increase in the duration and severity of the winter seasons (Luterbacher et al., 2004) accompanied by general colder temperatures from the start of the series (1500 CE) to the mid-nineteenth century (Leijonhufvud et al., 2010; Tarand and Nordli, 2001). The lower temperatures curtailed agricultural production by shortening plant growing seasons (Galloway, 1986; Zhang et al., 2011), which on occasions significantly affected society (Zhang et al., 2011).

Documented spatial and temporal heterogeneity within the LIA has promoted an ongoing debate on the forcing parameters that may have triggered this climate shift (Alonso-Garcia et al., 2017). The most commonly discussed mechanism refers to major changes in atmospheric dynamics driven by a combination of reduced solar irradiance and the occurrence of explosive volcanic eruptions (e.g. Bond et al., 2001; Miller et al., 2012; Moffa-Sánchez et al., 2014; PAGES 2k Consortium, 2013). Alternatively, internal dynamics of the oceanic and atmospheric circulation patterns (e.g. Mann et al., 2009; Trouet et al., 2009) or freshwater discharges to the North Atlantic (e.g. Alonso-Garcia et al., 2017; Manabe and Stouffer, 1995) have also played a major role in climate change, driving climate oscillation initially and then subsequently impacting sea surface circulation and deep water convection.

Content analysis of major ions contained in the Greenland Ice Sheet Project 2 (GISP 2) ice core shows elevated concentrations of sodium during the LIA (Mayewski et al., 1993), interpreted as being indicative of increased storminess in the region. This work proposes that the source for sea salt (sodium) during cooler periods was probably from ice-free (lower latitude) ocean, suggesting favoured meridional flow from lower latitudes to Greenland, which in turn was responsible for transferring energy poleward. Trouet et al. (2012), in an attempt to reconcile the apparent increase in storminess in the North Atlantic and reconstructed negative values of the North Atlantic Oscillation (NAO) index that dominated the LIA (Trouet et al., 2009), related the records of increased storminess during the LIA to more intense, rather than more frequent storms generated from the breakdown of blocking anticyclones. The NAO reconstruction by Trouet et al. (2009), and in particular, the shift from persistent positive NAO during the medieval period to negative values of the NAO as precursor of the shift to the LIA, were contested by other works showing instead positive phases, but not persistent positive values, during the thirteenth and fourteenth centuries (Ortega et al., 2015). The latter reconstruction documents variable values of the NAO during the LIA, despite three clear episodes dominated by negative values of the index (Ortega et al., 2015). Independently of the reconstructions of the NAO index, various works coincide to support, in agreement with the atmospheric circulation pattern suggested by Mayewski et al. (1993), the occurrence and likely dominance of atmospheric blocking events during LIA, highlighting their role on weakening the subpolar gyre (SPG) by changing the main route of westerlies (Moffa-Sánchez et al., 2014), transporting icebergs and sea ice (Alonso-Garcia et al., 2017), and sustaining its weaken regime after the shift (Moreno-Chamarro et al., 2017a). On the other hand, 'relative' blocking atmospheric conditions were also suggested by Costas et al. (2016) to explain the occurrence of windy events associated to the impact of storms across western Europe coasts in a context of relative cooling (Arctic amplification) over northernmost Atlantic. This pattern slightly contrasts with the persistent, blocked atmospheric conditions proposed by Moreno-Chamarro et al. (2017b), which implies the blocking of zonal circulation and thus might prevent the impact of westerlies across the western European coasts. In fact, considering present day reanalysis data, Trigo et al. (2004) concluded that during blocking episodes there is a lack of cyclones travelling over the northeastern Atlantic and Northern Europe. Most cyclones tend to move either along the western margin of the blocking pattern (between Greenland and the Arctic Sea) or through a southeasterly trajectory (between the Iberian Peninsula and the Caspian Sea). This pattern would explain the increase in storms in Greenland and the Iberian Peninsula, however, it remains unclear if this pattern could explain the suggested apparent simultaneous impact of storms across western European coasts during LIA (Costas et al., 2012; Costas et al., 2016).

3. Impacts of LIA over the western coast of Europe

Studies conducted on the geomorphological impact of the LIA on coastal systems include a wide range of examples from northern Europe and to a lesser extent from the south western Atlantic and Mediterranean coastal areas. As mentioned, aeolian activity related to the active migration of transgressive dunes during the LIA is by far its main geomorphological manifestation across western European coasts.

In addition to the well-documented active migration of transgressive dunes, the impact of the LIA across European coasts can be traced largely in coastal lagoons, as a consequence of marine inundation (i.e. overwash) of coastal lowlands. Case examples exist in the French Mediterranean coast (Degeai et al., 2015; Dezileau et al., 2011; Sabatier et al., 2012) or the northwest of the Iberian Peninsula (González-Villanueva et al., 2015); in estuaries, in NW France (Sorrel et al., 2009) or SW Italy (Budillon et al., 2005), in marshes as a consequence of the sedimentation of coarse-grained deposits (Poirier et al., 2017) or aeolian layers (Szkornik et al., 2008). Coastal barriers through the impact of extreme surge levels (Bateman et al., 2018; Cunningham et al., 2011; Jelgersma et al., 1995) provide further evidence of LIA related inundation. Also noteworthy is the relative lull in coastal plain progradation across Europe (Reimann et al., 2011).

Other works have focussed on detecting and analysing major changes in coastal areas by exploring the sedimentation patterns within coastal raised bogs (Björck and Clemmensen, 2004). The latter are shown through changes in the content of wind-transported clastic material within peat bogs and have been used to document periods of winter storminess during the LIA in southern Scandinavia (Björck and Clemmensen, 2004; de Jong et al., 2007), the Scottish Outer Hebrides (Orme et al., 2016) and Wales (Orme et al., 2015). The advantage of these works relative to other types of reconstructions is the expected continuity of the sedimentary record and its relatively high preservation, which in turn allows us to identify shifts within climate events such as the LIA. Nevertheless, all of these reconstructions inherently rely on the quality of the applied age model. Björck and Clemmensen (2004) identified three episodes within LIA dated at 1820 CE, 1650, 1550, 1500 (130, 300, 400 and 450 cal. Years BP), during which higher clastic content was identified, suggesting a greater impact of winter storms and enhanced atmospheric circulation, which the authors attributed to an expansion of the polar vortex. de Jong et al. (2007) identified two main phases within the LIA; an early, wetter phase dominated by zonal flow-driven winds from ca. 1180–1570 CE (770 to 380 cal. yrs BP), and a later drier phase dominated by meridional flow and more frequent atmospheric blocking from ca. 1650–1900 CE (300 to 50 cal. years BP). According to the authors, the greater aeolian influx of clastic materials, and thus aeolian activity, occurred during the shifts of these episodes, suggesting enhanced atmospheric circulation associated with these transitions. The analysis of peat bogs in the UK documents a generalised increase on the amount of sand delivered to these sinks from adjacent sandy coasts over the last 500 yrs. (Orme et al., 2015; Orme et al., 2016), despite a slight timing decoupling that could be explained by local differences (Orme et al., 2016). Two peaks (i.e. about 1370–1480 CE and 1740–1830) were identified within the analysed cores, suggesting a possible occurrence of intra-event shifts of the wind intensity.

Fig. 1 summarises documented storminess episodes from previous references. The work by Jackson et al., 2005 is also added to extend our discussion to Iceland as an additional source of information on aeolian activity and storminess on the fringes of Europe. The first implication that arises from Fig. 1 is that there is no clear temporal distribution of storminess within the LIA, nor a distinct spatial distribution of their occurrence. This suggests that the storminess signal during the LIA was both temporally and spatially variable despite a relative difference in time of occurrence between northern and southern sites. Northern sites appear to show a greater concentration of storminess before 1600 CE, reducing from 8 sites where signs of storminess are evident to an average of 3 sites. Alternatively, the few examples from southern Europe document enhanced storminess only after 1500 CE, however, the reduced number of sites inhibits the identification of any spatial groupiness pattern. Nevertheless, the period between 1400 CE and 1800 is a key storm period for Europe.

3.1. Impacts of the LIA on coastal dunes

Regarding the active formation and migration of transgressive coastal dunes during the LIA, it has been acknowledged as the last major mobilization phase of aeolian sand across western European coasts (Clarke and Rendell, 2009; Clemmensen and Murray, 2006; Costas et al., 2016). Examples of active transgressive dunes moving inland, driven by enhanced storminess can be found in Sweden (Szkornik et al., 2008), Denmark (Aagaard et al., 2007; Clemmensen et al., 2015; Clemmensen and Murray, 2006), Great Britain (Bampton et al., 2017; Gilbertson et al., 1999; Sommerville et al., 2007; Sommerville et al., 2001), Northern Ireland (Wilson and Braley, 1997; Wilson et al., 2004), the Netherlands (Jelgersma and Altena, 1969), SW France (Bertran et al., 2011; Clarke et al., 2002), Northern France (Van Vliet-Lanoë et al., 2017), Northern Portugal (Clarke and Rendell, 2006; Costas et al., 2013) and centre of Portugal (Clarke and Rendell, 2006; Costas et al., 2012; Costas et al., 2016). Fig. 2 compiles the age of these moving dunes during the LIA. Considered ages were preferably determined by OSL on transgressive dunes in order to be able to compare episodes of sand movement rather than non-movement intervals through analysis of interbedded soils. The temporal distribution of documented episodes of sand movement again indicates, a greater concentration of information within higher latitude countries, and an apparent continuous aeolian activity across the LIA. However, in the frequency of obtained ages, a pattern can be identified that suggests an increase in aeolian activity starting after 1400 CE with a maximum around 1600, and a new and greater increase after 1700 CE that then reverts after 1900 CE (see Fig. 3). The latter is in close agreement with the periods of more frequent and spatially coherent storminess episodes. Despite the limited number of ages within southern dunes, they suggest that aeolian activity was ubiquitous across western European coasts.

Despite the inconsistent temporal and spatial pattern in the results, it is worth noting a gradual decrease in the number of dunes assigned to the early LIA when compared with the number of ages that have been associated with a late phase of the LIA (Fig. 3). This might be a result of bias in the sediment sampling, or a consequence of the recycling of the aeolian deposits as they could start moving earlier in time, but some units might only stop their advance during the latter years of the event.

Many examples in the literature exploring inland aeolian sand drift during the LIA, focus on the consequences of this active migration of coastal dunes over coastal human settlements. They describe the encroachment and eventual abandonment of a number of coastal villages across western European coasts. These events may have resulted from isolated extreme wind storms as in 1413 when one such event submerged the village of Forvie (NE Scotland), under 30 m of sand (Griffiths, 2015). However, most cases resulted from the cumulative effect of windy or stormy periods, lasting from weeks to months (e.g. Kenfig; Brown (2015)). These sand drift events led to the eventual abandonment of agricultural lands, churches and settlements (Cornwall, UK), harbours (e.g. Rattray in Scotland), farmlands and entire villages (Broo in Shetland Islands). Historical accounts are numerous in the western coast of Britain, although episodes in the eastern coast of Britain, France and Portugal can also be found in the literature (Fig. 4). If this information is compared with the ages we have from OSL dating, the main signature that comes out is the fact that events recorded by these different sources happen out of phase with historical records pointing towards earlier ages (most frequent between 1300 CE and 1600), but coincident with enhanced storminess across northern Europe (Fig. 1). The latter could be explained by two different reasons, the first has been already discussed earlier and is related to the possibility of earlier dunes being remobilized, resetting their clock. The second could be explained by the fact that once abandon, burial occurrences are no longer recorded, or to the additional human impact over some of the sites?

The explanation for the occurrence of such events is in general,

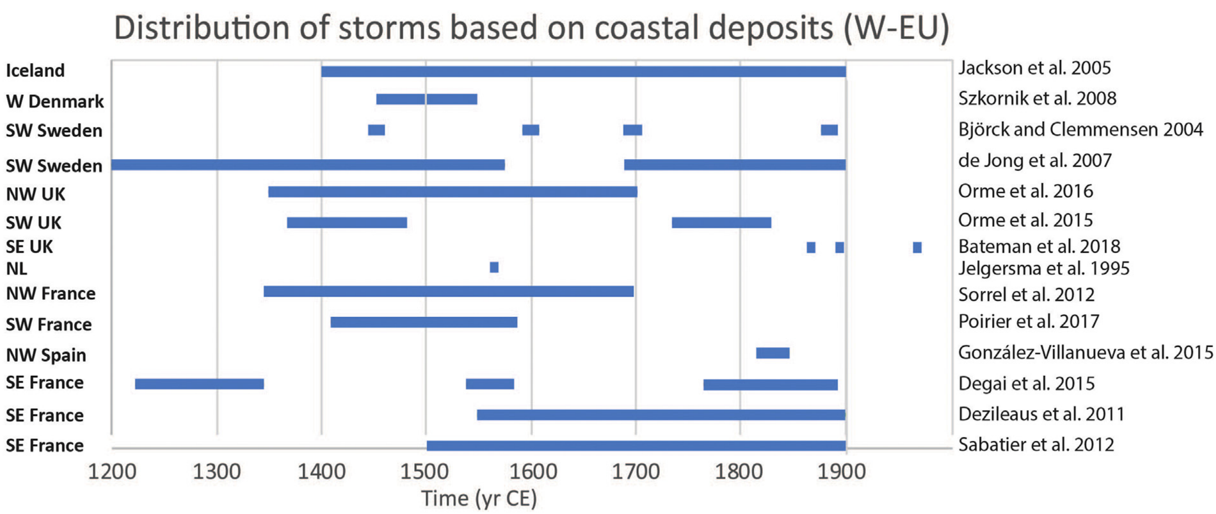

Fig. 1. Summary of documented storminess episodes from previous works for Europe (Jackson et al. (2005) is also added to extend our discussion to Iceland as an additional source of information). Note there no clear temporal distribution of storminess within the LIA, nor a distinct spatial distribution of their occurrence.

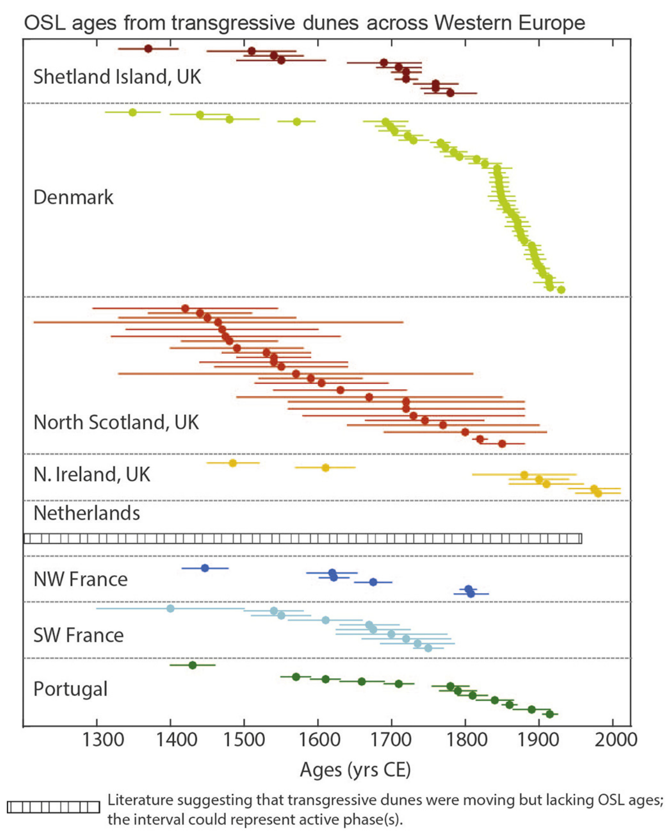

Fig. 2. Spatial and temporal distribution of active transgressive dunes identified in the literature. The dots indicate the age of the samples found in the literature at each analysed site at Shetland Islands (Bampton et al., 2017), Denmark (Aagaard et al., 2007; Clemmensen et al., 2015; Clemmensen and Murray, 2006), North and West Scotland (Gilbertson et al., 1999; Sommerville et al., 2007), Northern Ireland (Wilson and Braley, 1997; Wilson et al., 2004), Northern France (Van Vliet-Lanoë et al., 2017), Southwestern France (Bertran et al., 2011; Clarke et al., 2002), and Portugal (Clarke and Rendell, 2006; Costas et al., 2012), including the error bars. The white boxed bar is based on literature suggesting that transgressive dunes were moving during that time interval. N.B.OSL dates do not indicate the duration of the aeolian pulse representingthe time elapsed since last exposure or active phase(s) (Jelgersma and van Regteren Altena, 1969).

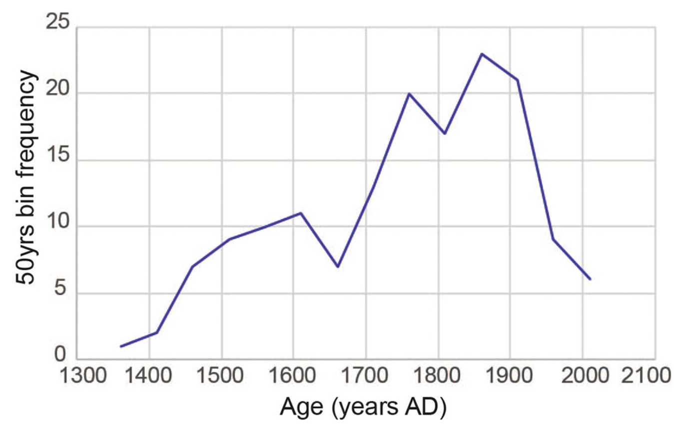

Fig. 3. Frequency distribution over time of OSL ages found within the literature (see Fig. 2). Bin size used was 50 yrs. as a compromise between data smoothing and still definition of major peaks.

rather vague with storms among the most frequently referred drivers for the active migration of transgressive dunes (e.g. Clarke and Rendell, 2009; Clemmensen and Murray, 2006; Costas et al., 2016), combined with rising (e.g. Aagaard et al., 2007) or falling (e.g. Orford et al., 2000) sea levels to explain associated changes in sediment supply. Some works state that the movement of sand and consequently the burial of coastal settlements cannot be solely attributed to storms but to a combination of factors (Bampton et al., 2017; Brown, 2015; Griffiths, 2015), among which the impact of human activities on the landscape is also included as a relevant factor. In particular, Orme et al. (2016) and (Bateman and Godby, 2004) suggest enhanced human landscape modification over dune vegetation may promote instability and therefore easier transference inland, within a frame of intensified winds. In many cases, during the climate deterioration associated with the onset of the LIA, human activity contributed to the loss of vegetation cover, exacerbating the movement of sand. Reports on practices such as removal of marram grass on dunes (e.g. village of Culbin; Griffiths (2015)), over-grazing and poor land management or the introduction of rabbits (Bampton et al., 2017) could all have had a contribution to accelerating sand encroachment.

4. Conceptual model for LIA-induced dune dynamics

Despite the large number of works examining the intensity of

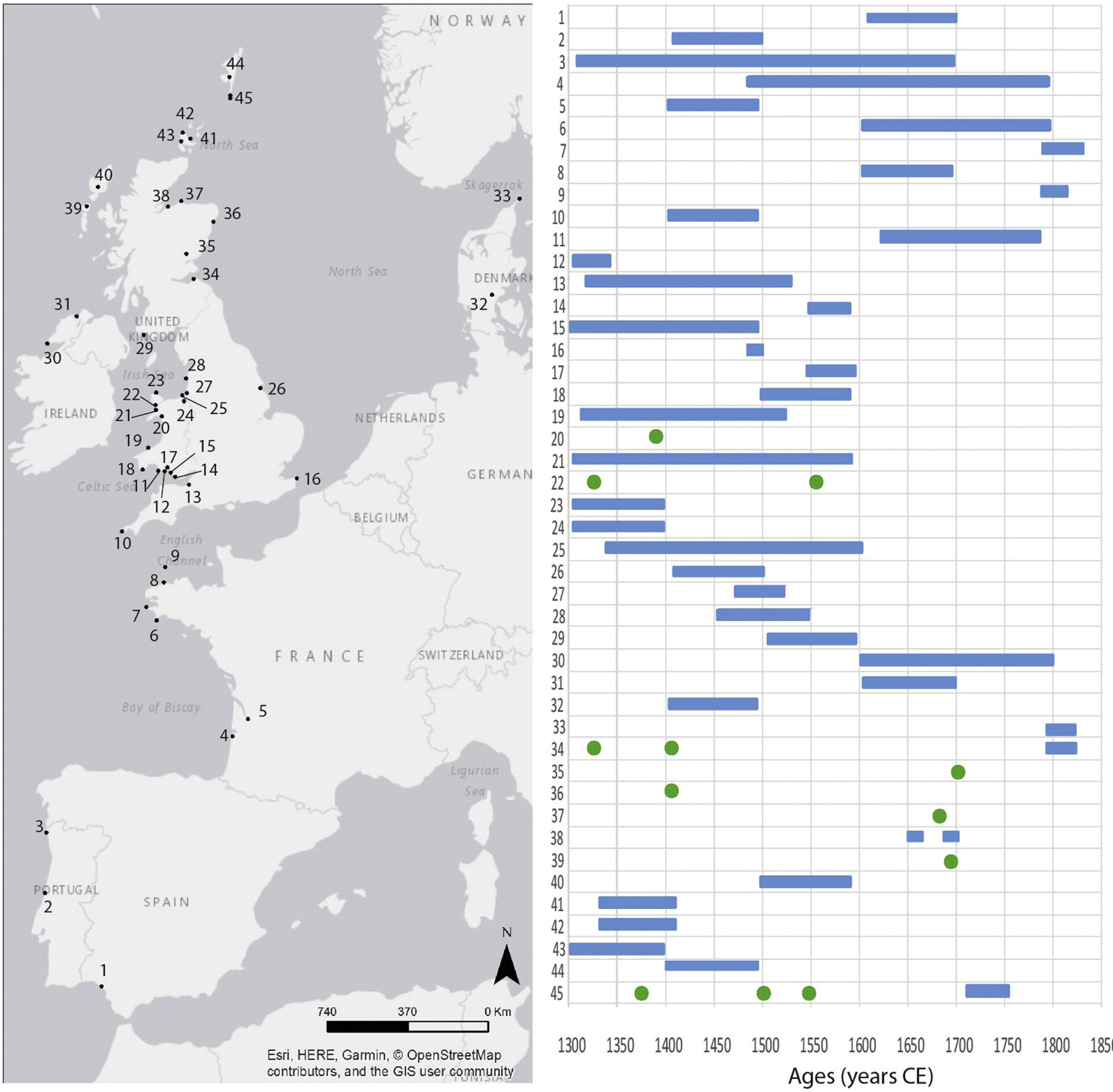

Fig. 4. Spatial and temporal distribution of historical events of sand invasion across the western coast of Europe. Blue lines represent years of sand invasion episodes for a specific site and green dots represent isolated sand-storm events. Numbers correspond to reported locations of sand encroachment as follows: 1) Huelva/Cádiz (Borja et al., 1999); 2)Marihna Grande (Pinto, 1938); 3) Fao and Chafé (Granja and Soares de Carvalho, 1992); 4) Bordeoux, 5) Aquitanie (Clarke et al., 2002); 6) Brittany (Meur et al., 2002); 7) South Brittany, 9) Batz Island, 33) Skagen (Van Vliet-Lanoe¨ et al. 2017 and references therein); 8) San Pol de Leon (Clarke and Rendall, 2011 and references therein); 10) Cornwall (Clarke and Rendall, 2009 and references therein); 11) Rhossili, 12) Pennard, 13) Berrow, 15) Merthyr Mawr, 17) Penmaen, 18) Stackpole, 19) Y Ferwig, 21) Llys Rhosyr, 22) Newborough, 25) Meols, 26) Flixborough, 29) Glenluce, 41) Sandhill, 42) Pierowall, 43) Bay of Skaill (Brown., 2015 and references therein); 16) Sandwich (Sommerville, 2003); 27) Sefton, 28) Lancashire (Pye and Nield, 1993); 23) Anglesey, 32) Jutland, 40) Outer Hebrides (Clarke and Rendall, 2009 and references therein); 14) Kenfig, 20) Harlech, 24) Cheshire, 34) Eldbote, 35) Rattray, 36) Forvi, 37) Hindform (Griffiths, 2015 and references therein); 30) Donegal/Sligo/Mayo (Wilson, 1990), 31) Mullaghmore/Horn Head; 38) Culbin, 39) North Uist, 44) Orkney & Shetland (Lamb and Frydendahl, 1991); 45) Broo (Bampton et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

aeolian activity on European coasts during the LIA, few investigate the causes that may have promoted this large-scale movement of sand inland. Most examples attributed this aeolian activity to:

- higher frequency or intensity of storms during the LIA, which in turn may have a significant influence on wind power, vegetation and sediment supply to the coast (Clarke et al., 2002; Clarke and Rendell, 2006; Clarke and Rendell, 2009; Costas et al., 2012);.
- rising sea level and enhanced storminess, promoting the supply of sediment to the emerged shore (Aagaard et al., 2007);
- falling sea level and storminess, promoting the exposure of large areas of sand (Christiansen and Bowman, 1986; Clemmensen et al.,

1996; Orford et al., 2000; Wilson et al., 2004; Wilson et al., 2001);

- climate oscillations and human activities, destabilizing the vegetation cover (Jelgersma and Altena, 1969; Lamb and Frydendahl, 1991).

The above list presents four simplified scenarios that may explain the onset and subsequent movement of transgressive dunes during the LIA as a consquence of storms, sea-level or climate oscillations, and/or human impact. Clarke and Rendell (2009) claimed a unique regional factor (i.e. storminess) to explain the onset and evolution of this event across European coasts based on the match between higher frequency storm occurrence and aeolian activity, however, it is still not clear if this can be explained by storms alone.

An increase on the frequency and intensity of the storms appears as a common element in all the scenarios, in combination, however, with other factors such as an increase on the wind regime and oscillations of sea level. Evidence of inland sand migration based on OSL ages used across a variety of transgressive dune systems in Europe (Fig. 2) and their coincidence with periods of increase storminess (Fig. 1) suggest a predominant role for coastal storms in the development of these systems. However, in those cases with heavily vegetated dunes, the effect of just storms would not be enough to invoke widespread destabilisation of vegetation cover and therefore an additional factor should be introduced to explain the shift from fixed to mobile systems. Here, we suggest the effect of lower temperatures and its corresponding decrease in the vegetation growth season (Jackson and Cooper, 2011). The latter may also actually have impacted the growth and development of vegetation in dunes (*Ammophila arenaria* seedling germination and rhizome growth curtailed see: Chergui et al., 2018), and thus, combined with destructive storms, could have triggered the widespread rollover of coastal dunes during this cold climate event with devastating consequences for coastal populations such as sand encroachment over villages and crops (Fig. 4). Based on these, here, we propose a new conceptual model of LIA-induced transgressive dune behaviour, focussing on a general dune field behavioural approach where environmental drivers (mainly storminess and temperature oscillations) push the dunes into various stages involving a number of feed-back loops within the system (Fig. 5).

The conceptual model proposed goes through different stages from stable and vegetated dunes towards instability of the system and the development of a mobile transgressive dune system. However, since the LIA has been described in the literature as a discontinuous climatic swing (Mann, 2002), stages proposed need to be understood in the context of continuous pauses and temporal reversals between stages but with a net direction onto stage V of system recovery towards the end of the LIA period.

4.1. Stage I

Stage I of the model (Fig. 5, stage I) represents a scenario of relatively stable and likely heavily vegetated coastal dune systems previous to the LIA. Under this stage modal wave climate and wind regime are presumed with no significant oscillations in temperature. This stage also represents the scenario of system recovery after the LIA onset or intra LIA phases in which a stabilisation of dune field is reached (temporarily) due to a decrease in storminess and an increase in temperature for sustained periods, allowing temporary re-vegetation growth to occur.

4.2. Stage II

The onset of the LIA then sees a pattern of increased storminess developing along with lower ambient temperatures. Impacts then occur initially on the frontal (seaward) edges of dune fields, where storm wave erosion occurs more frequently than normal and salt spray generally increases salt content on and within the sand along the back beach areas (Stage II.A.). Seedlings (particularly of *Ammophila sp.*) are intolerant of salt with lethal levels being at 1.5% (Benecke, 1930). This will dramatically reduce the potential of post-storm recovery and lead to unstable and less vegetated foredune zones. Increased storminess will see strong, sand-laden winds carry sand from the beaches resulting in high burial rates of vegetation, likely at levels where regrowth cannot keep pace with sand deposition, effectively swamping and stunting binding vegetation. Parallel to these is a decrease in atmospheric air temperatures that reduce the annual growing season of vegetation, would promote less vigorous vegetative growth and therefore destabilised sediment within the eroded backbeach/foredune zones. In Stage II·B, formation of blowouts are driven by this instability and eventual fragmentation of foredunes occur, stripping vegetation and there is an increase in strong onshore storm winds.

4.3. Stage III

The weakened and fragmented by blowouts foredune and backbeach areas become so unstable that they develop into strong source areas of aeolian sand and rapidly inundate landward dunes, moving as mobile sand sheets. Other features such as blowouts and high parabolic dunes are likely to be more prevalent and thus help to intensify the destabilisation phase of the dunes, channelling sand inland. Rapid sand inundation will further promote over-burial of vegetation and the zone of de-stabilisation expands to quickly envelop the dune field into a transgressive and highly mobile system. Decreased temperatures will also support this instability, where vegetative growth is much more suppressed and fixing of wind-blown sand is therefore hugely reduced.

4.4. Stage IV

Dunes are now in a fully transgressive and sparsely vegetated state made up of various dune types representative of the distance inland, sediment supply and wind regime present. As the system moves towards this fully transgressive state, parabolic dunes assume lower width to length ratios, and effectively are stretched ('smeared') across the landscape as sand availability reduces with inland distance. If the destabilisation process is rapid, then it is likely that large (high) dunes undergo a 'rollover' where only the top sections of the dune system are destabilised and highly mobile, cascading over the top of the dune field. The lower levels might remain largely out of reach of the LIA-induced transgressive dune mobility. As a consequence, dune fields that were made up of lower elevation dune forms may have been completely rolled over during the LIA and effectively being 'peeled back' down to the water table at the seaward edges if new sediment supply was not available from the beach.

4.5. Stage V

Climate amelioration towards the end of LIA, or during intra-LIA stages, might induce increasing temperatures and less storminess, setting into motion a recovery of the dune system into a more stabilised stage. Vegetation growing seasons expand and calmer wind conditions promote vegetation growth and sand eventually becomes more locked into fixed dune forms. Mobile parabolic dunes and blowouts rapidly revegetate and largely fixed in position. Some front edge instability may still persist and will be some of the last zones to be revegetated in the dune system, sustained by higher parabolic dune forms (more difficult to vegetate) and through occasional wave erosion events.

5. Discussion & conclusions

The Little Ice Age is one of the most noted climatological events in recent history, appearing in many historical annals and playing a significant role in natural and anthropogenic dynamics, particularly in the northern hemisphere. Much has been written on its occurrence and

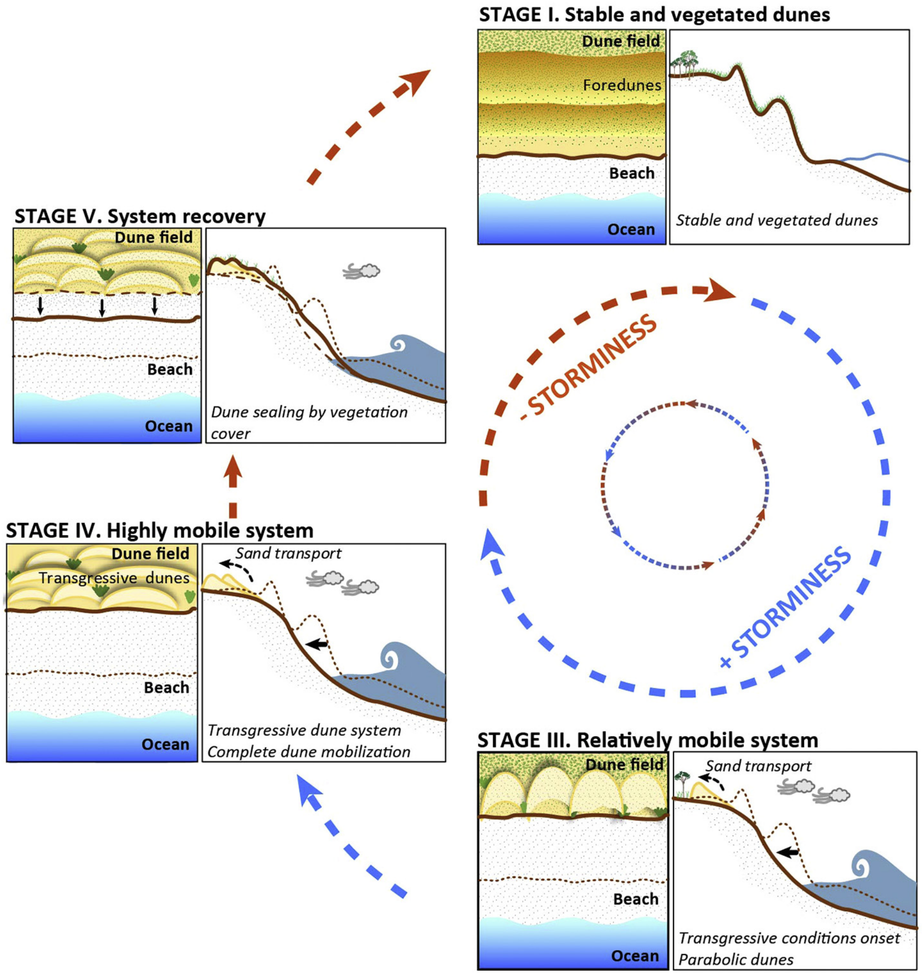

Fig. 5. Conceptual model proposed for large scale coastal dune behaviour during the LIA. The conceptual model includes five stages of behaviour from an early stage of stable and vegetated dunes before LIA onset (stage I) towards a series of processes that could have increased the instability of the dune system, resulting in a highly un-vegetated mobile system (stage IV). Transition between stages is driven by a combination of storminess and other parameters that could induce pauses and temporal reversals between stages as it is indicated by the internal circle. Stages II A & B represent early phases of dune instability with front edge of coastal dunes supplying the initial pulse of aeolian activity with stage III progressing into stage IV fully transgressive. Stage IV then eventually recedes into stage V of system recovery and stability afterwards.

environmental impacts. Sediments locked within dune systems and subsequently released through the onset of conditions associated with the LIA, have been noted in numerous studies but these have focused largely on localised case examples with little wider implications for dune dynamics and specifics of dune field behaviour.

The LIA in Europe resulted in largescale transgressive coastal dune behaviour and manifested in a relocation of huge volumes of sand from the coastal hinterland to inland accommodation space when available. This effectively helped to 'perch' vast quantities of dune sand into many land-locked elevations and locations, stranding significant parts of the littoral sediment budget away from marine processes. In those areas where sediment supply was finite this would have had an pivotal impact on coasts and greatly affected their level of resilience to storms, likely making them more vulnerable to erosion from frequent, high intensity storms. This would have led to yet further accelerated coastal erosion, loss of vegetated foredunes and destabilized frontal edges of dune systems at the time of the LIA, further accentuating transgressive dune behaviour.

The widespread mobilization of aeolian sand during the LIA, has been attributed to the impact of enhanced storminess occurring during this climate event (e.g. Clarke and Rendell, 2009; Costas et al., 2016; Van Vliet-Lanoë et al., 2017). Yet, aeolian activity has been also used as a proxy to derive episodes of enhanced storminess (e.g. Costas et al., 2016; Trouet et al., 2012), assuming the later premise. The storminess record compiled here from different coastal records points towards a not so clear relation between storminess periods and aeolian activity. The first shows that the occurrence of storminess could be spatially different across the LIA with areas at higher latitudes recording the impact of enhanced storminess earlier in time relative to lower latitudes. Conversely, the distribution of aeolian activity from dated sediments across western Europe does not show a clear spatial distribution, but instead, a rather continuous process across the whole climate event despite some periods of reduced activity as suggested by the occurrence of temporal gaps in between obtained ages (although this may also be down to a simple lack of studies in certain regions). The latter could be also interpreted as a sign of the rapid response of coastal dunes to climate events. However, any further discussion will always be limited to the number of samples, and to the bias on the sampling, with more recently activated dunes being more frequently and/or easily dated. OSL dates are showing younger ages relative to historic accounts because they represent sediments that were last exposed to light and therefore they are the most recent phases of activity. Similarly, documented burial of villages appears to have concentrated around earlier ages at greater latitudes when compared with the OSL estimated ages of mobile dunes. The latter suggests a relative temporal disagreement between the OSL determined ages and the historical records. However, this difference could be easily explained by the fact that some of the affected villages were finally abandoned after years of battling against sand encroachment.

The above highlights the limitations that can be raised when trying to establish the spatial and temporal distribution of storm events across western Europe, despite the importance of these features tracking the impact of this climate event. Additionally, the increase in aeolian activity, even with its significant impact on coastal communities, has not yet been fully assessed. Several works have attempted to explain the onset of such massive dune mobilization across Europe, relating it to the onset of storminess periods, relative changes in sea level, or even human activities. However, very few (Aagaard et al., 2007; Szkornik et al., 2008) have explicitly explained the actual process through which sand is made available for the wind to be blown by the resultant strong winds. In fact, to date, no model has been put forward to explain the temporal behaviour of coastal dune dynamics spanning the onset of the LIA and its subsequent evolution into a fully transgressive behaviour and back to its eventual restoration to 'normal' conditions again. Our model proposes a *conceptual* framework by which dune fields initially disintegrated into highly mobile dune fields at the beginning of the LIA and continued this instability for significant (century scale) periods over the LIA until a stage of climate amelioration allowed the system to re-stabilise. We propose a range of states for which the dunes moved through (Fig. 5) and associated dune types and features likely to have been developed in each phase.

When dune fields are effectively 'turned over' in this fashion, we may have seen the top sections of the dunes being reworked down as far as the water table and anything lower than that not reached by new aeolian action due to the binding effects of the water table itself. This created a two-tiered dune 'cake' within modern coastal dunes within Europe, the top sections effectively only 5–600 years old as per OSL dating, with sediments re-exposed to light during the LIA 'turnover' and lower sections dating to several thousand years BP which were not reached by the LIA epoch (see example stratigraphy at Costas et al. (2012)). The newly turned over dunescape would have been re-sculpted during the LIA and modern dune surface topographies may now not resemble their pre-LIA dune field surfaces.

The onset of the LIA (Phase II A & B) cannot be attributed to only a single parameter (such as an increase in storminess) but may well have been forced by a myriad of events and associated changes in environmental variables. Obvious candidates for triggering instability of the dunes are higher frequency and higher magnitude storm events and eroding and destabilizing coastal foredunes. The higher levels of salt spray and associated substrate content within that zone would also have reduced (or eliminated) the pioneer plant species from germinating, depleted vegetation growth and created a more sparse foredune system. This would have led to more active aeolian transport and left the dunes less vegetated, creating less resilient frontal dunes to wave attack. In combination with this, a general decline in ambient temperature associated with the LIA onset would have lessened the growing season (i.e. is the part of the year during which local weather conditions, rainfall and temperature, permit normal plant growth) of dune plant species. A reduced growing season would have resulted in less vegetation cover and therefore potentially more mobile dune forms. Once dunes are much less vegetated, the role of wind intensity would be much more significant and strong winds associated with more frequent and intensified storm levels would induce catastrophic failures in the dune field integrity shifting them into a transgressive and highly mobile dune state (Phase IV).

Stage V of the model, where dune recovery takes hold is also likely to have had distinct latitudinal variability, depending on the 'retreat rate' of LIA's reach. Although there is no clear evidence of it, the LIA probably retreated gradually, receding with a northward retreat path, as suggested by the OSL compiled ages, which show that northern sites stopped moving relatively later on.

Enhancement of dune mobility during LIA by human activities (uprooting, introduction of rabbits, overgrazing of dune due to decrease of vegetation in grazing areas), although not explicitly within our proposed model, has to be a considered factor in any proposed conceptualization of the response of the dunes to the LIA as it could have contributed to a declining vegetation cover. In turn, and in order to combat inland sand invasion, coastal communities also initiated a series of actions for stabilizing the dunes by the end of the XVIII century across Europe (e.g. Brown, 2015; Clemmensen and Murray, 2006; Danielsen et al., 2012; De Keyzer and Bateman, 2018; Tastet and Pontee, 1998). However, and probably, due to the persistence of favorable conditions for dune migration, these actions only successfully fixed the dunes within the first half of the 20th century, probably once LIA finished or it was towards its end, and in addition, the management practices were more efficient including larger hectares of afforestation. The latter were likely coincident with the last phases of stage IV/V of the model proposed here.

Regarding dune response, it is likely that dunes during stage IV were entering into a less dynamic phase, though the speed of this stage may have been much more rapid than the shift from Stage I. Jackson and Cooper (2011) for example, have shown rapid decadal revegetation patterns across Irish dunes, demonstrating that dune systems can quickly switch to more fixed states if conditions such as increasing growing seasons are rapidly altering to higher extremes. Tsoar (2005) also showed that dunes are much more difficult to destabilise once they are fixed compared to stabilisation of mobile systems. The latter also implies that clockwise shifts within the conceptual model might happen more easily than anticlockwise shifts, in particular during the first stages.

The formation of transgressive dunes, characteristic of this time interval, can be confused with the growth of different types of coastal dunes, namely foredunes, if they are not explicitly referred to and only the mention of enhanced aeolian activity is included. This fact is very relevant as the formation or growth mechanisms behind both systems are radically different, thus it is important to discriminate between regressive (foredunes) and transgressive coastal dunes. Regressive dunes evolve in pace with shoreline evolution and they are represented by foredunes of diverse dimensions depending on the beach sediment budget (Davidson-Arnott et al., 2018; Psuty, 2004). Conversely, transgressive sheets and dune fields are large-scale, mobile, partially, and fully vegetated coastal dune fields that, when active, migrate transversely, obliquely or alongshore depending on the regional wind regime (Hesp, 2013). Hesp (2013), in his review on the evolution of coastal transgressive dune fields, developed conceptual models that synthesize the main scenarios of dune development and subsequent evolutionary paths. Some of which, have been also described within previous works exploring the onset of transgressive dunes during the LIA in Europe.

It is likely that latitudinal variation may have existed in the relative importance of fundamental drivers in the model. For higher latitude dune fields, one driver may have been temperature changes, which can affect the growth rate of vegetation species' holding the dune fields in place. An accentuated decrease in temperature in more northerly latitudes was reconstructed by Mann et al. (2009), who found that cooling during LIA was strongest in the north, and weaker at southerly latitudes. Similarly, Moreno-Chamarro et al. (2017b) showed an amplification of winter cooling over central and northern continental Europe. For lower latitudes (e.g. Spain and Portugal) however, windiness may have been a more important determinant of dune field activity, where the temperature swings would have been less severe. Sparse vegetation (and species variation) in southern dunes may have made them less resilient and thus may have had a more rapid response to increases in wind speeds. Likewise, when dunes in a more northerly dune setting entered into the advanced transgressive stage III phase, winds may have reverted to be the more dominant factor in maintaining dune mobility.

Overall, we can view the LIA as a major widespread climate event significantly altering the coastal dune landscape of Europe and after the initial emplacement of sediment from the retreating ice sheets of the last ice age represents the most important environmental event to have affected European coastal dunes.

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References

Aagaard, T., Orford, J., Murray, A.S., 2007. Environmental controls on coastal dune formation; Skallingen Spit, Denmark. Geomorphology 83 (1–2), 29–47.
Alonso-Garcia, M., Kleiven, H., McManus, J.F., Moffa-Sanchez, P., Broecker, W.S., Flower, B.P., 2017. Freshening of the Labrador Sea as a trigger for Little Ice Age development. Clim. Past 13 (4), 317–331.
Bampton, M., Kelley, A., Kelley, J., Jones, M., Bigelow, G., 2017. Little Ice Age catastrophic storms and the destruction of a Shetland Island community. J. Archaeol. Sci. 87, 17–29.
Bateman, M.D., Godby, S.P., 2004. Late-Holocene inland dune activity in the UK: a case study from Breckland, East Anglia. The Holocene 14 (4), 579–588.
Bateman, M.D., Rushby, G., Stein, S., Ashurst, R.A., Stevenson, D., Jones, J.M., Gehrels, W.R., 2018. Can sand dunes be used to study historic storm events? Earth Surf. Process. Landf. 43 (4), 779–790.
Benecke, W., 1930. Zur Biologieder Strand und Diinenflora 1. Vergleichende Versuche über die Salztoleranz van Ammophila arenaria Link, Elymus arenarius L. und Agriopyrum junceum L. Ber. Deut. Bol. Ges. 48, 127–139.
Bertran, P., Bateman, M.D., Hernandez, M., Mercier, N., Millet, D., Sitzia, L., Tastet, J.-P., 2011. Inland aeolian deposits of south-west France: facies, stratigraphy and chronology. J. Quat. Sci. 26 (4), 374–388.
Björck, S., Clemmensen, L.B., 2004. Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia? The Holocene 14 (5), 677–688.
Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial Climates. Science 278 (5341), 1257–1266.
Bond, G.C., Showers, W., Elliot, M., Evans, M., Lotti, R., Hajdas, I., Bonani, G., Johnson, S., 1999. The North Atlantic's 1-2 Kyr climate rhythm: relation to Heinrich events, Dansgaard/Oeschger Cycles and the Little Ice Age. In: Clark, P.U., Webb, R.S., Keigwin, L.D. (Eds.), Mechanisms of Global Climate Change at Millennial Time Scales. American Geophysical Union, pp. 35–59.
Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent Solar Influence on North Atlantic Climate During the Holocene. Science 294 (5549), 2130–2136.
Brown, P.J., 2015. Coasts of catastrophe? The incidence and impact of aeolian sand on British medieval coastal communities. Eur. J. Post Class. Archaeol. 5, 127–148.
Budillon, F., Esposito, E., Iorio, M., Pelosi, N., Porfido, S., Violante, C., 2005. The geological record of storm events over the last 1000 years in the Salerno Bay (Southern Tyrrhenian Sea): new proxy evidences. Adv. Geosci. 2, 123–130.
Chergui, A., Zakariya, I., Nejjari, R., El Hafid, L., Melhaoui, M., 2018. Int. J. Appl. Environ. Sci. 13 (7), 633–642.
Christiansen, C., Bowman, D., 1986. Sea-level changes, coastal dune building and sand drift, North-Western Jutland, Denmark. Geogr. Tidsskrift-Danish J. Geogr. 86 (1), 28–31.
Clarke, M.L., Rendell, H.M., 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal. The Holocene 16 (3), 341–355.
Clarke, M.L., Rendell, H.M., 2009. The impact of North Atlantic storminess on western European coasts: a review. Quat. Int. 195 (1–2), 31–41.
Clarke, M., Rendell, H., Tastet, J.-P., Clave, B., Masse, L., 2002. Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine Coast, southwest France. The Holocene 12 (2), 231–238.
Clemmensen, L.B., Murray, A., 2006. The termination of the last major phase of aeolian sand movement, coastal dunefields, Denmark. Earth Surf. Process. Landf. 31 (7), 795–808.
Clemmensen, L.B., Andreasen, F., Nielsen, S.T., Sten, E., 1996. The late Holocene coastal dunefield at Vejers, Denmark: characteristics, sand budget and depositional dynamics. Geomorphology 17 (1–3), 79–98.
Clemmensen, L.B., Glad, A.C., Hansen, K.W.T., Murray, A.S., 2015. Episodes of aeolian sand movement on a large spit system (Skagen Odde, Denmark) and North Atlantic storminess during the Little Ice Age. Bull. Geol. Soc. Den. 63, 17–28.
Costas, S., Jerez, S., Trigo, R.M., Goble, R., Rebêlo, L., 2012. Sand invasion along the Portuguese coast forced by westerly shifts during cold climate events. Quat. Sci. Rev. 42 (0), 15–28.
Costas, S., Brito, P., Fitzgerald, D., Goble, R., 2013. Climate-driven episodes of dune mobilization and barrier growth along the central coast of Portugal. Geol. Soc. Lond., Spec. Publ. 388.
Costas, S., Naughton, F., Goble, R., Renssen, H., 2016. Windiness spells in SW Europe since the last glacial maximum. Earth Planet. Sci. Lett. 436, 82–92.
Cunningham, A.C., Bakker, M.A.J., van Heteren, S., van der Valk, B., van der Spek, A.J.F., Schaart, D.R., Wallinga, J., 2011. Extracting storm-surge data from coastal dunes for improved assessment of flood risk. Geology 39 (11), 1063–1066.
Danielsen, R., Castilho, A.M., Dinis, P.A., Almeida, A.C., Callapez, P.M., 2012. Holocene interplay between a dune field and coastal lakes in the Quiaios– Tocha region, central littoral Portugal. The Holocene 22 (4), 383–395.
Davidson-Arnott, R., Hesp, P., Ollerhead, J., Walker, I., Bauer, B., Delgado-Fernandez, I., Smyth, T., 2018. Sediment Budget Controls on Foredune Height: comparing simulation model results with field data. Earth Surf. Proc. Landforms. https://doi.org/10.1002/esp.4354. (n/a-n/a).
Dawson, A.G., Hickey, K., Mayewski, P.A., Nesje, A., 2007. Greenland (GISP2) ice core and historical indicators of complex North Atlantic climate changes during the fourteenth century. The Holocene 17 (4), 427–434.
De Keyzer, M., Bateman, M.D., 2018. Late Holocene landscape instability in the Breckland (England) drift sands. Geomorphology 323, 123–134.
Degeai, J.-P., Devillers, B., Dezileau, L., Oueslati, H., Bony, G., 2015. Major storm periods and climate forcing in the Western Mediterranean during the Late Holocene. Quat. Sci. Rev. 129, 37–56.
Dezileau, L., Sabatier, P., Blanchemanche, P., Joly, B., Swingedouw, D., Cassou, C., Castaings, J., Martinez, P., Von Grafenstein, U., 2011. Intense storm activity during the Little Ice Age on the French Mediterranean coast. Palaeogeogr. Palaeoclimatol. Palaeoecol. 299 (1–2), 289–297.
Fagan, B., 2000. The Little Ice Age: How Climate Made History, 1300–1850. Basic Books.
Fedorowicz, S., Wysiecka, G., Zieliński, P., Hołub, B., 2012. Phases of aeolian accumulation on the Vistula Spit (Southern Baltic Sea) in the light of TL dating and analysis of a digital elevation model. Geol. Quart. 56 (2).
Galloway, P.R., 1986. Long-term fluctuations in climate and population in the Preindustrial Era. Popul. Dev. Rev. 12 (1), 1–24.
Gilbertson, D.D., Schwenninger, J.L., Kemp, R.A., Rhodes, E.J., 1999. Sand-drift and soil formation along an exposed North Atlantic Coastline: 14,000 years of diverse geomorphological, climatic and human impacts. J. Archaeol. Sci. 26 (4), 439–469.
González-Villanueva, R., Pérez-Arlucea, M., Costas, S., Bao, R., Otero, X.L., Goble, R., 2015. 8000 years of environmental evolution of barrier–lagoon systems emplaced in coastal embayments (NW Iberia). The Holocene 25 (11), 1786–1801. https://doi.org/10.1177/0959683615591351.
Griffiths, D., 2015. Medieval Coastal Sand Inundation in Britain and Ireland. Mediev. Archaeol. 59 (1), 103–121.
Grove, J.M., 2001. The initiation of the "Little Ice Age" in regions round the North Atlantic. Clim. Chang. 48 (1), 53–82.
Grove, J., 2004. Little Ice Ages: Ancient and Modern. Routledge, New York.
Hesp, A.P., 2013. Conceptual models of the evolution of transgressive dune field systems. Geomorphology 199, 138–149.
Hofstede, J.L.A., 1991. Sea level rise in the inner German Bight Since AD 600 and its implications upon tidal flats geomorphology. In: Brückner, Radtke (Eds.), Von der Nordsee bis zum Indischen Ozean. Franz Steiner Verlag, Stuttgart, pp. 11–27.
Jackson, D.W.T., Cooper, J.A.G., 2011. Coastal dune fields in Ireland: rapid regional response to climatic change. J. Coast. Res. SI (64), 293–297.
Jackson, M.G., Oskarsson, N., Trønnes, R.G., McManus, J.F., Oppo, D.W., Grönvold, K., Hart, S.R., Sachs, J.P., 2005. Holocene loess deposition in Iceland: evidence for millennial-scale atmosphere-ocean coupling in the North Atlantic. Geology 33 (6), 509–512.
Jelgersma, S., Altena, J.F.V.R., 1969. An outline of geological history of the coastal dunes in the western Netherlands. Geol. Mijnb. 48 (3), 335–342.
Jelgersma, S., van Regteren Altena, J.F., 1969. An outline of the geological history of the coastal dunes in the western Netherlands. Geol. Mijnb. 48, 335–342.
Jelgersma, S., Stive, M.J.F., van der Valk, L., 1995. Holocene storm surge signatures in the coastal dunes of the western Netherlands. Mar. Geol. 125 (1), 95–110.
de Jong, R., Schoning, K., Björck, S., 2007. Increased aeolian activity during humidity shifts as recorded in a raised bog in south-est Sweden during the past 1700 years. Clim. Past 3, 411–422.
Lamb, H.H., 1984. Some studies of the Little Ice Age of recent centuries and its great storms. In: Mörner, N., Karlén, W. (Eds.), Climatic Changes on a Yearly to Millennial Basis. Springer, Dordrecht.
Lamb, H., Frydendahl, K., 1991. Historic Storms of the North Sea. Cambridge University Press, British Isles and Northwest Europe.
Leijonhufvud, L., Wilson, R., Moberg, A., Söderberg, J., Retsö, D., Söderlind, U., 2010. Five centuries of Stockholm winter/spring temperatures reconstructed from documentary evidence and instrumental observations. Clim. Chang. 101 (1), 109–141.
Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., Wanner, H., 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303 (5663), 1499–1503.
Manabe, S., Stouffer, R.J., 1995. Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. Nature 378, 165.
Mann, M.E., 2002. Little Ice Age. In: MacCracken, M.C., Perry, J.S. (Eds.), The Earth system: physical and chemical dimensions of global environmental change. Encyclopedia of Global Environmental Change. John Wiley & Sons, Ltd, Chichester, pp. 504–509.
Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the Little Ice Age and medieval climate anomaly. Science 326 (5957), 1256–1260.
Matthews, J.A., Briffa, K.R., 2005. The 'little ice age': re-evaluation of an evolving concept. Geogr. Annal. Ser. A Phys. Geogr. 87 (1), 17–36.
Mayewski, P.A., Meeker, L.D., Morrison, M.C., Twickler, M.S., Whitlow, S.I., Ferland, K.K., Meese, D.A., Legrand, M.R., Steffensen, J.P., 1993. Greenland ice core "signal" characteristics: an expanded view of climate change. J. Geophys. Res. Atmos. 98

(D7), 12839–12847.
deMenocal, P., Bond, G., 1997. Holocene climate less stable than previously thought. Eos, Transac. Am. Geophys. Union 78 (41), 447–454.
Miller, G.H., Geirsdóttir, Á., Zhong, Y., Larsen, D.J., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Refsnider, K.A., Lehman, S.J., Southon, J.R., Anderson, C., Björnsson, H., Thordarson, T., 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. Geophys. Res. Lett. 39 (2), L02708.
Moffa-Sánchez, P., Born, A., Hall, I.R., Thornalley, D.J.R., Barker, S., 2014. Solar forcing of North Atlantic surface temperature and salinity over the past millennium. Nat. Geosci. 7, 275.
Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., Jungclaus, J.H., 2017a. An abrupt weakening of the subpolar gyre as trigger of Little Ice Age-type episodes. Clim. Dyn. 48 (3), 727–744.
Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., Luterbacher, J., Jungclaus, J.H., 2017b. Winter amplification of the European Little Ice Age cooling by the subpolar gyre. Sci. Rep. 7 (1), 9981.
Nesje, A., Dahl, S.O., 2003. The 'Little Ice Age' – only temperature? The Holocene 13 (1), 139–145.
Nielsen, P.R., Dahl, S.O., Jansen, H.L., 2016. Mid- to late Holocene aeolian activity recorded in a coastal dunefield and lacustrine sediments on Andøya, northern Norway. The Holocene 26 (9), 1486–1501.
Orford, J.D., Wilson, P., Wintle, A.G., Knight, J., Braley, S., 2000. Holocene coastal dune initiation in Northumberland and Norfolk, eastern UK; climate and sea-level changes as possible forcing agents for dune initiation Holocene land-ocean interaction and environmental change around the North Sea. Geological Society Special Publications, pp. 197–217.
Orme, L.C., Davies, S.J., Duller, G.A.T., 2015. Reconstructed centennial variability of Late Holocene storminess from Cors Fochno, Wales, UK. J. Quat. Sci. 30 (5), 478–488.
Orme, L.C., Reinhardt, L., Jones, R.T., Charman, D.J., Barkwith, A., Ellis, M.A., 2016. Aeolian sediment reconstructions from the Scottish Outer Hebrides: late Holocene storminess and the role of the North Atlantic Oscillation. Quat. Sci. Rev. 132, 15–25.
Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C.C., Casado, M., Yiou, P., 2015. A model-tested North Atlantic Oscillation reconstruction for the past millennium. Nature 523, 71.
PAGES 2k Consortium, 2013. Continental-scale temperature variability during the past two millennia. Nat. Geosci. 6, 339.
Pierik, H.J., van Lanen, R.J., Gouw-Bouman, M.T., Groenewoudt, B.J., Wallinga, J., Hoek, W.Z., 2018. Controls on late-Holocene drift-sand dynamics: The dominant role of human pressure in the Netherlands. The Holocene 0 (0) 0959683618777052.
Poirier, C., Tessier, B., Chaumillon, E., 2017. Climate control on late Holocene high-energy sedimentation along coasts of the northeastern Atlantic Ocean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 485, 784–797.
Psuty, N.P., 2004. The coastal foredune: A morphological basis for regional coastal dune development. In: ML, M., NP, P. (Eds.), Coastal Dunes, Ecology and Conservation. Ecological Studies, vol. 171. Springer-Verlag, Berlin, pp. 11–27.
Reimann, T., Tsukamoto, S., Harff, J., Osadczuk, K., Frechen, M., 2011. Reconstruction of Holocene coastal foredune progradation using luminescence dating — An example from the Świna barrier (southern Baltic Sea, NW Poland). Geomorphology 132 (1–2), 1–16.
Sabatier, P., Dezileau, L., Colin, C., Briqueu, L., Bouchette, F., Martinez, P., Siani, G., Raynal, O., Von Grafenstein, U., 2012. 7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events. Quat. Res. 77 (1), 1–11.
Sommerville, A.A., Sanderson, D.C.W., Hansom, J.D., Housley, R.A., 2001. Luminescence dating of aeolian sands from archaeological sites in Northern Britain: a preliminary study. Quat. Sci. Rev. 20 (5), 913–919.
Sommerville, A.A., Hansom, J.D., Housley, R.A., Sanderson, D.C.W., 2007. Optically stimulated luminescence (OSL) dating of coastal aeolian sand accumulation in Sanday, Orkney Islands, Scotland. The Holocene 17 (5), 627–637.
Sorrel, P., Tessier, B., Demory, F., Delsinne, N. and Mouazé, D., 2009. Evidence for millennial-scale climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine estuary (NW France). Quat. Sci. Rev., 28(5–6): 499–516.
Szkornik, K., Gehrels, W.R., Murray, A.S., 2008. Aeolian sand movement and relative sea-level rise in Ho Bugt, western Denmark, during the `Little Ice Age. The Holocene 18 (6), 951–965.
Tarand, A., Nordli, P.Ø., 2001. The Tallinn temperature series reconstructed back half a millennium by use of proxy data. In: Ogilvie, A.E.J., Jónsson, T. (Eds.), The Iceberg in the Mist: Northern Research in Pursuit of a "Little Ice Age". Springer Netherlands, Dordrecht, pp. 189–199.
Tastet, J.-P., Pontee, N.I., 1998. Morpho-chronology of coastal dunes in Médoc. A new interpretation of Holocene dunes in Southwestern France. Geomorphology 25 (1–2), 93–109.
Trigo, R.M., Trigo, I.F., DaCamara, C.C., Osborn, T.J., 2004. Climate impact of the European winter blocking episodes from the NCEP/NCAR Reanalyses. Clim. Dyn. 23 (1), 17–28.
Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic oscillation mode dominated the medieval climate anomaly. Science 324 (5923), 78–80.
Trouet, V., Scourse, J.D., Raible, C.C., 2012. North Atlantic storminess and Atlantic Meridional overturning circulation during the last millennium: reconciling contradictory proxy records of NAO variability. Glob. Planet. Chang. 84–85 (0), 48–55.
Tsoar, H., 2005. Sand dunes mobility and stability in relation to climate. Phys. A Stat. Mech. Appl. 357 (1), 50–56.
Van Vliet-Lanoë, B., Goslin, J., Hénaff, A., Hallégouët, B., Delacourt, C., Le Cornec, E., Meurisse-Fort, M., 2016. Holocene formation and evolution of coastal dunes ridges, Brittany (France). Compt. Rendus Geosci. 348 (6), 462–470.
Van Vliet-Lanoë, B., Lauer, T., Meurisse-Fort, M., Gosselin, G., Frechen, M., 2017. Late Holocene coastal dune activity along the Dover Strait, Northern France – Insights into Middle Ages and Little Ice Age coastal dynamics constrained by optically stimulated luminescence dating. Z. Dtsch. Ges. Geowiss. 168 (1), 53–66.
Wallinga, J., van Mourik, J.M., Schilder, M.L.M., 2013. Identifying and dating buried micropodzols in Subatlantic polycyclic drift sands. Quat. Int. 306, 60–70.
Wanner, H., Mercolli, L., Grosjean, M., Ritz, S.P., 2015. Holocene climate variability and change; a data-based review. J. Geol. Soc. 172 (2), 254–263.
Wilson, P., Braley, S.M., 1997. Development and age structure of Holocene coastal sand dunes at Horn Head, near Dunfanaghy, Co Donegal, Ireland. The Holocene 7 (2), 187–197.
Wilson, P., Orford, J.D., Knight, J., Braley, S.M., Wintle, A.G., 2001. Late-Holocene (post-4000 years BP) coastal dune development in Northumberland, northeast England. The Holocene 11 (2), 215–229.
Wilson, P., McGourty, J., Bateman, M.D., 2004. Mid-to late-Holocene coastal dune event stratigraphy for the north coast of Northern Ireland. The Holocene 14 (3), 406–416.
Wintle, A.G., Clarke, M.L., Musson, F.M., Orford, J.D., Devoy, R.J.N., 1998. Luminescence dating of recent dunes on Inch Spit, Dingle Bay, southwest Ireland. The Holocene 8 (3), 331–339.
Zhang, D.D., Lee, H.F., Wang, C., Li, B., Pei, Q., Zhang, J., An, Y., 2011. The causality analysis of climate change and large-scale human crisis. Proc. Natl. Acad. Sci. 108 (42), 17296–17301.